# Precession as Probe of the Neutron Star Core

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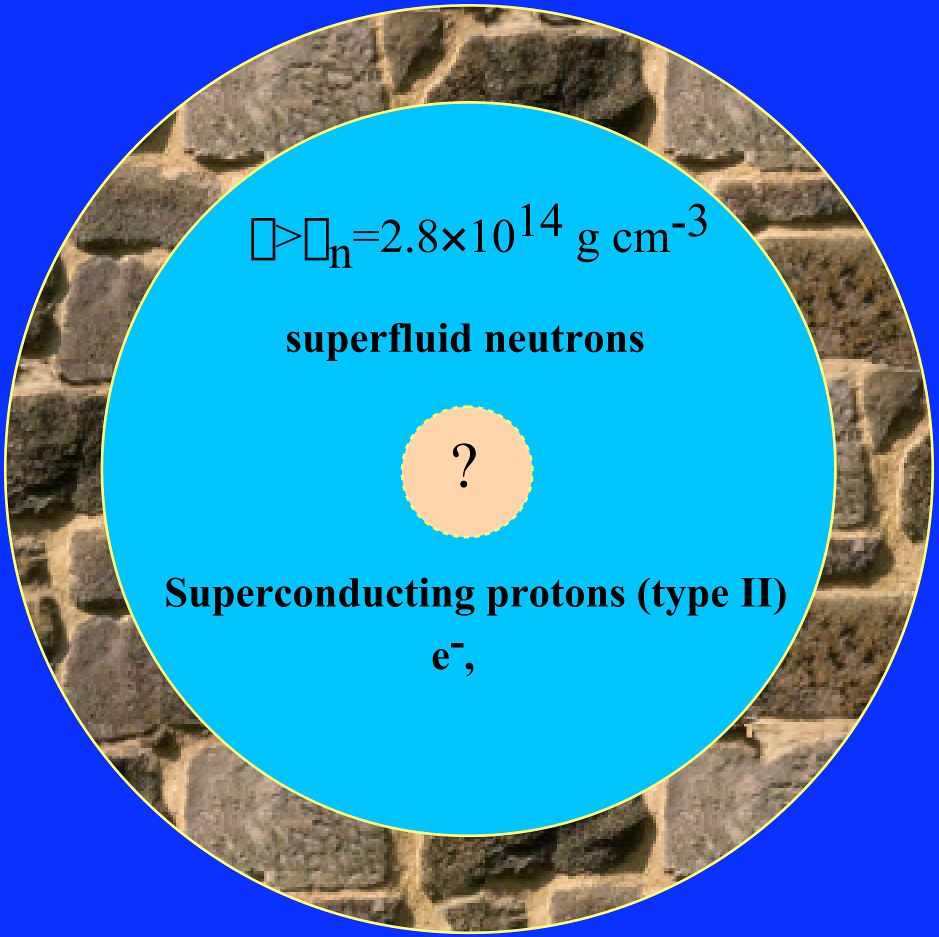
## Overview

Evidence that neutron stars precess.

Probing the state of the liquid interior.

<u>Conclusion:</u> *the standard picture of the neutron star core might require revision.*

# The standard picture of the core



# Precession as a Probe of the Interior

- Precession is a mode of the system. It is a perturbation about the state of minimum rotational energy (for given L).
- The manner in which a body precesses depends (in part) on internal dynamics.

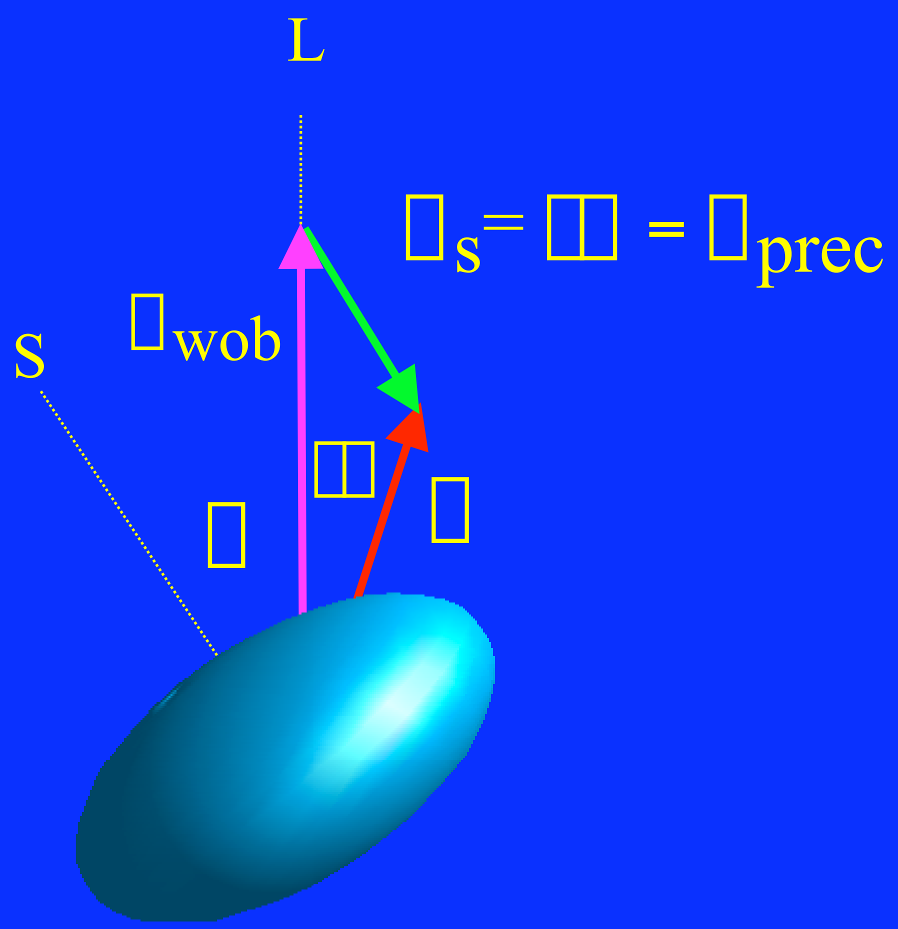
$\Rightarrow$ Observations can be used to constrain the state of the interior.

It is a different kind of probe than thermal evolution, glitches, M, R.

# Free precession:
## rigid, oblate biaxial object

□=□I/I<<1

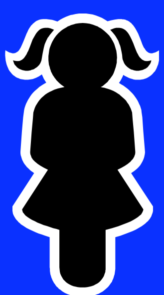
□ = "wobble angle"

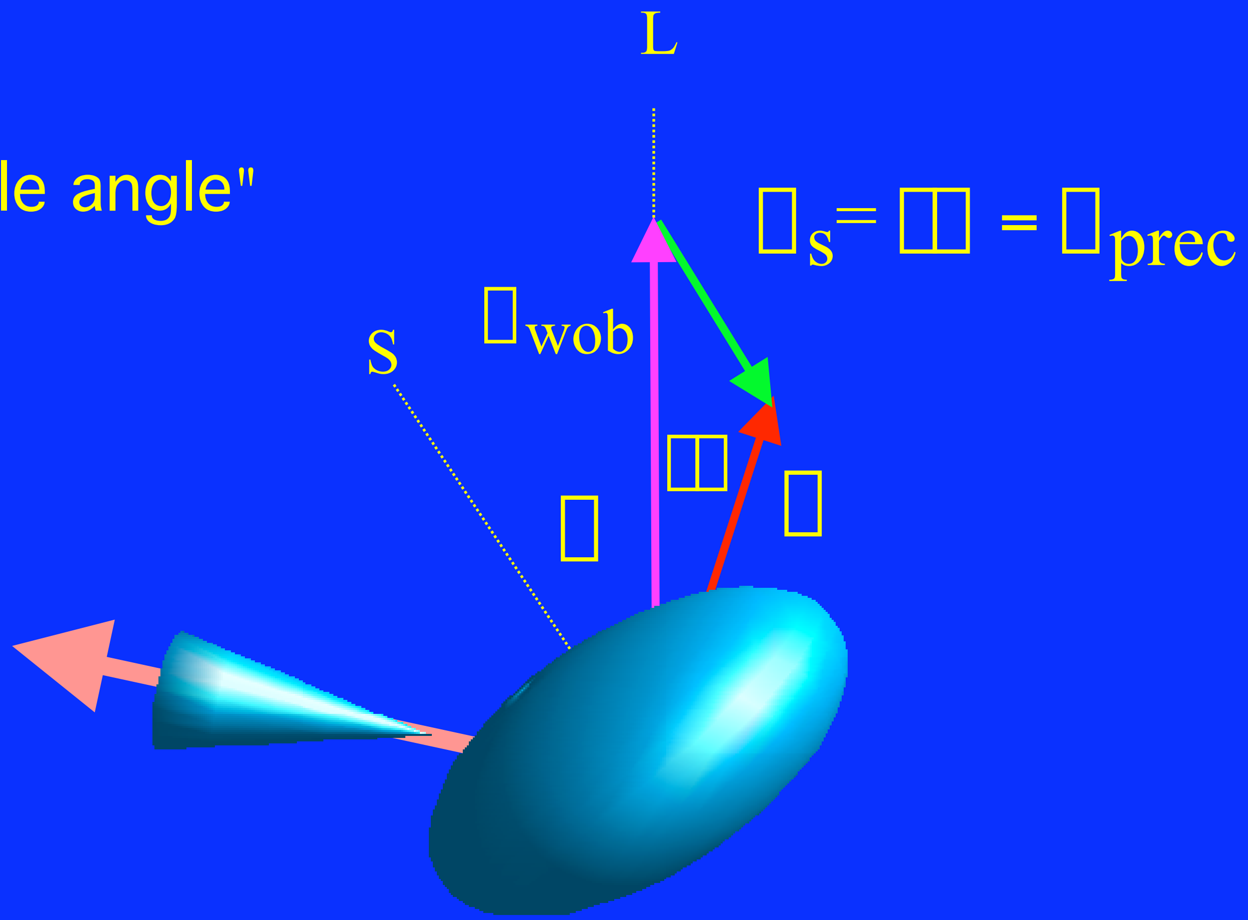


# Free precession:
## rigid, oblate biaxial object

[illegible]=[illegible]I/I<<1

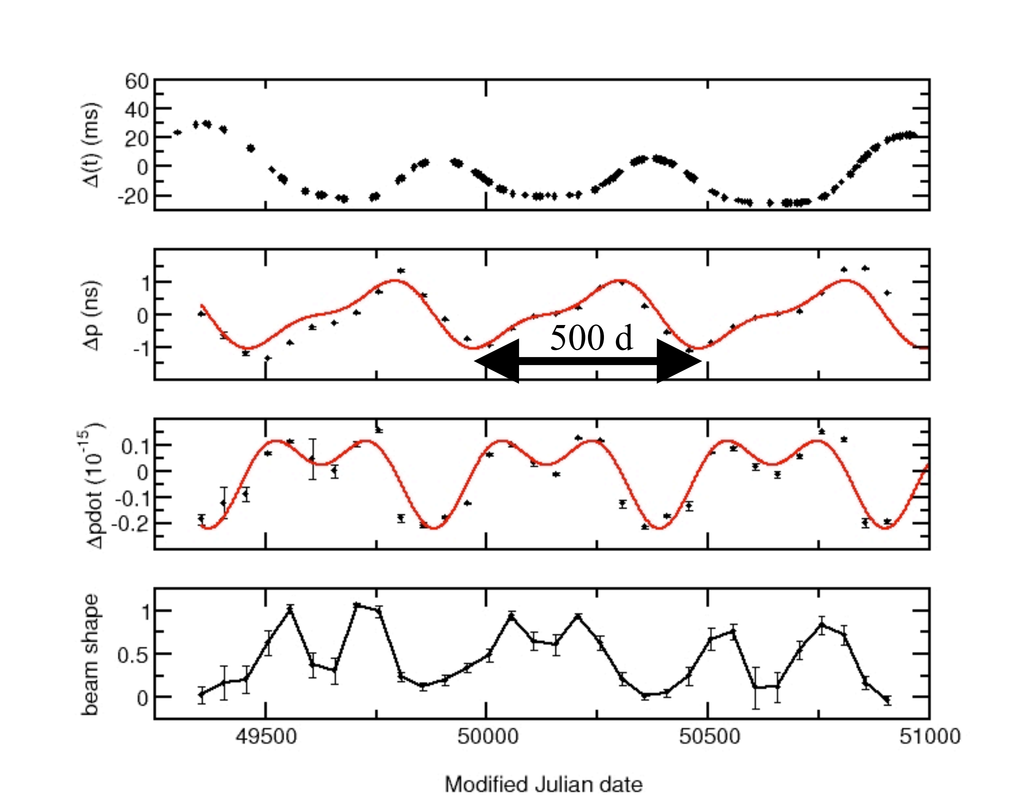
[illegible] = "wobble angle"



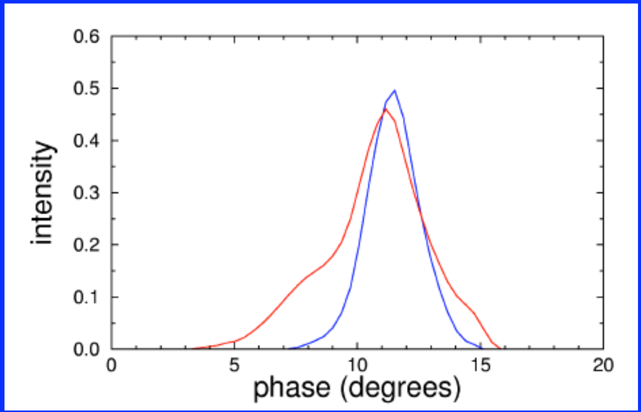



The observer sees variations in pulse arrival times and beam width.

# Observational Evidence for Precession: PSR B1828-11
(Stairs, Lyne & Shemar 2000)




- Periodic timing.
- Correlated changes in beam width.



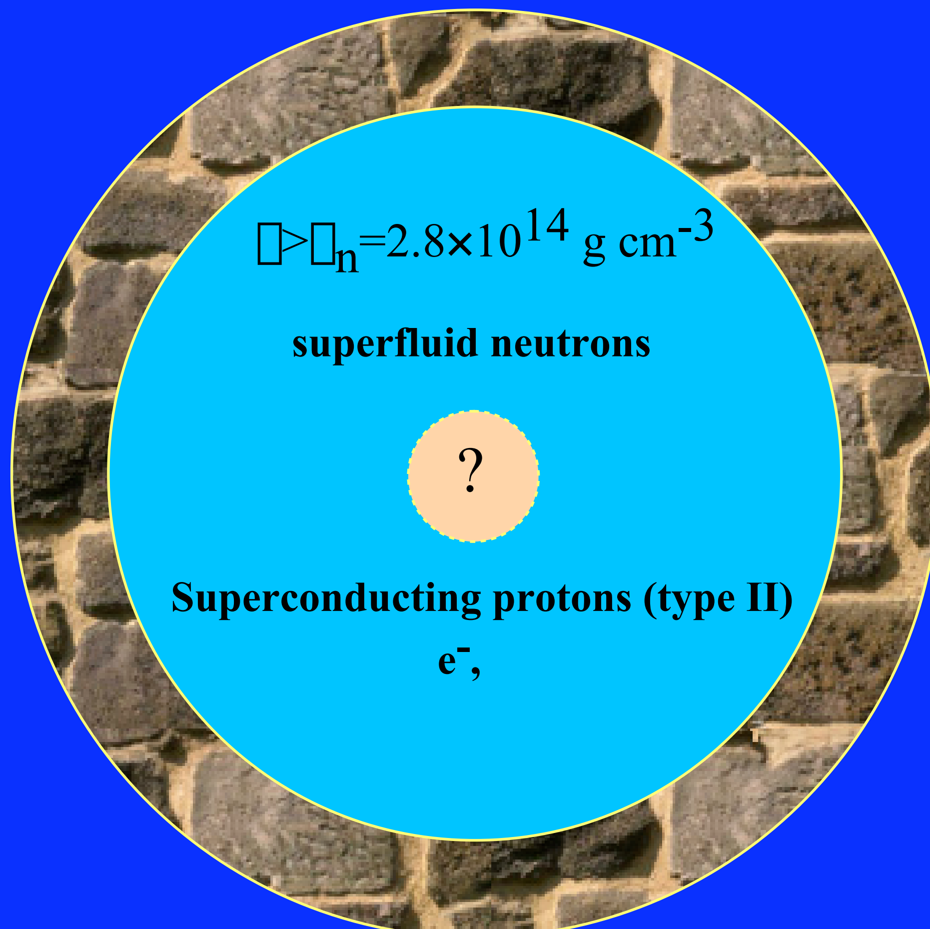
# PSR B1828-11

- Fits to timing data, assuming rigid-body rotation and dipole torque, indicate a wobble angle of $\simeq 3$ deg.
- Deformation of $\epsilon \equiv \Delta I/I \simeq 10^{-8}$.

(Link & Epstein 2001)

# Constraining the state of the liquid core

Nucleon pairing calculations predict...



# What is the core liquid doing, and how does it affect precession?


"Bert's inner core is spinning on its own."

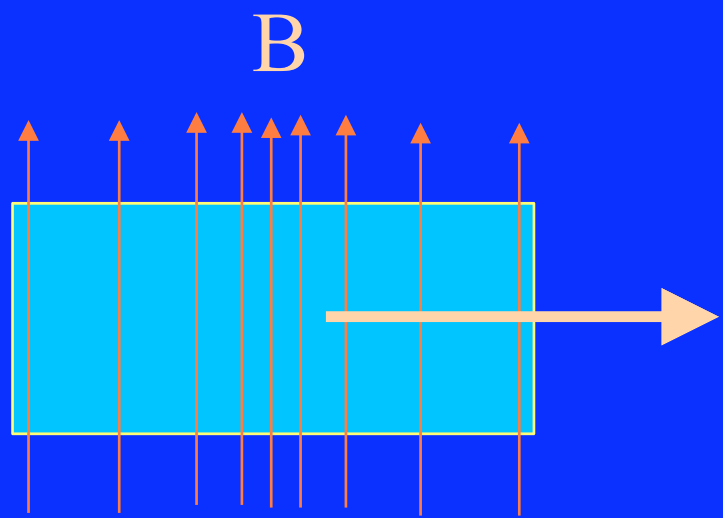
## A star can precess only if a portion of its figure cannot follow the instantaneous spin axis

If excited, precession could occur if:

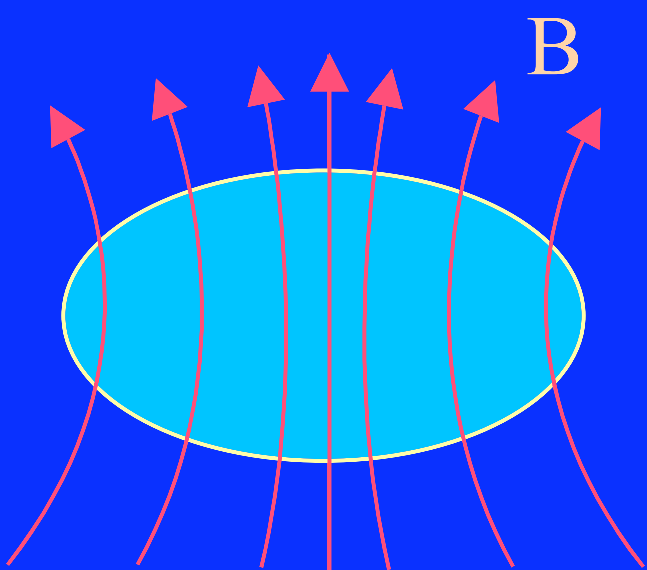
- Crust rigidity sustains deformation (Ushomirsky, Cutler & Link 2003).
- The internal magnetic field significantly deforms the star (Bonazzola & Gourgoulhon 1996; Wasserman 2003).

# The magnetic field deforms the star

(Bonazzola & Gourgoulhon 1996)



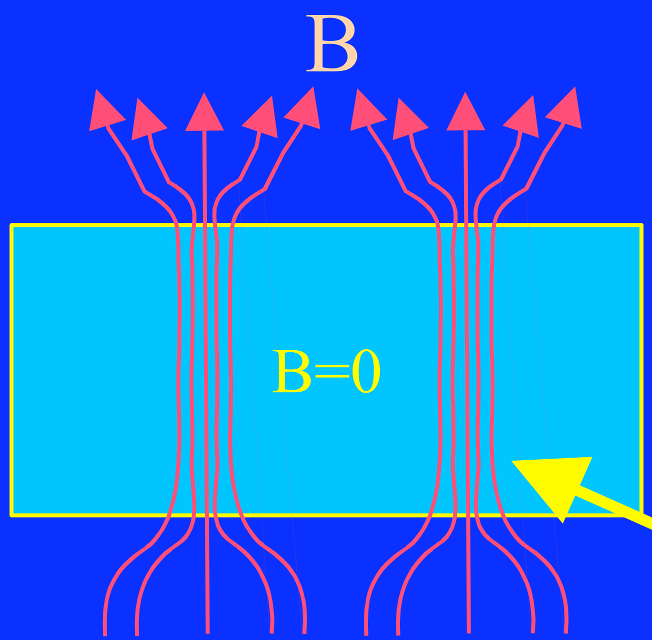

$$\square P_B = \square \frac{B^2}{8\Pi}$$




$$\square \sim \frac{P_B}{P} \sim \frac{B^2 R^4}{GM^2} \sim 10^{-10} \to P_{prec} \sim 100 \text{ yr}$$

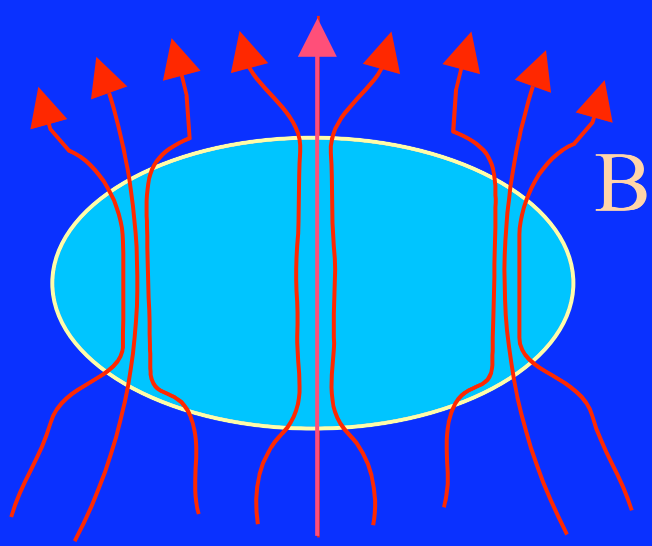
# Deformation of a Type II superconducting core

(Wasserman 2003)



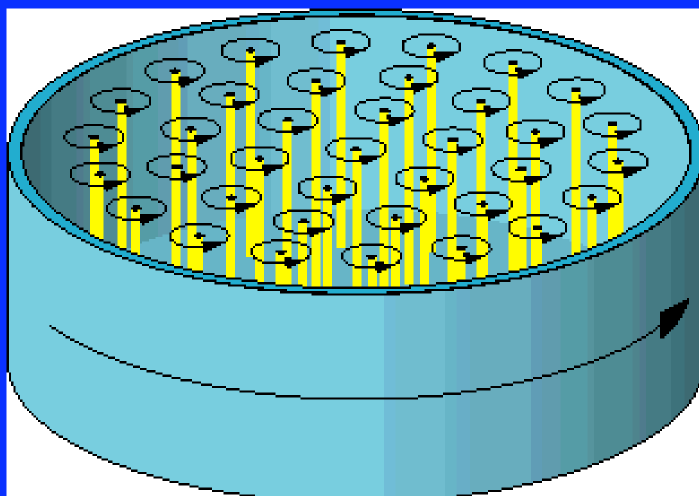

The Maxwell stress is larger by a factor of ~$H_c/B$~100.

$B=H_c \square 10^{15}$ G

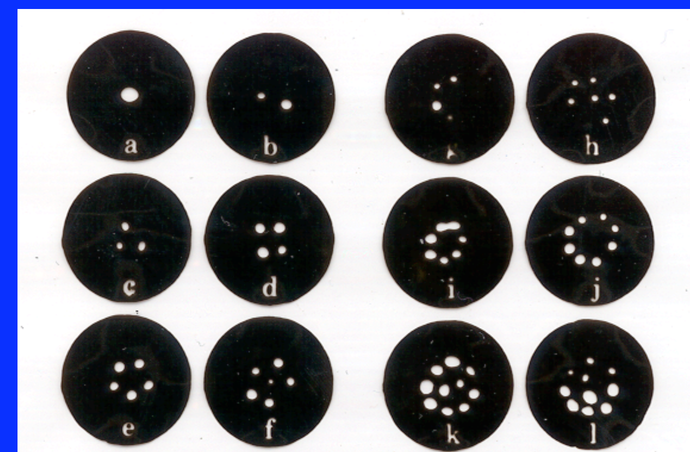



$$\square \sim \frac{P_B}{P} \sim \frac{H_c B R^4}{G M^2} \sim 10^{-8} \rightarrow P_{prec} \sim 1 \text{ yr}$$

# The neutron superfluid's rotation



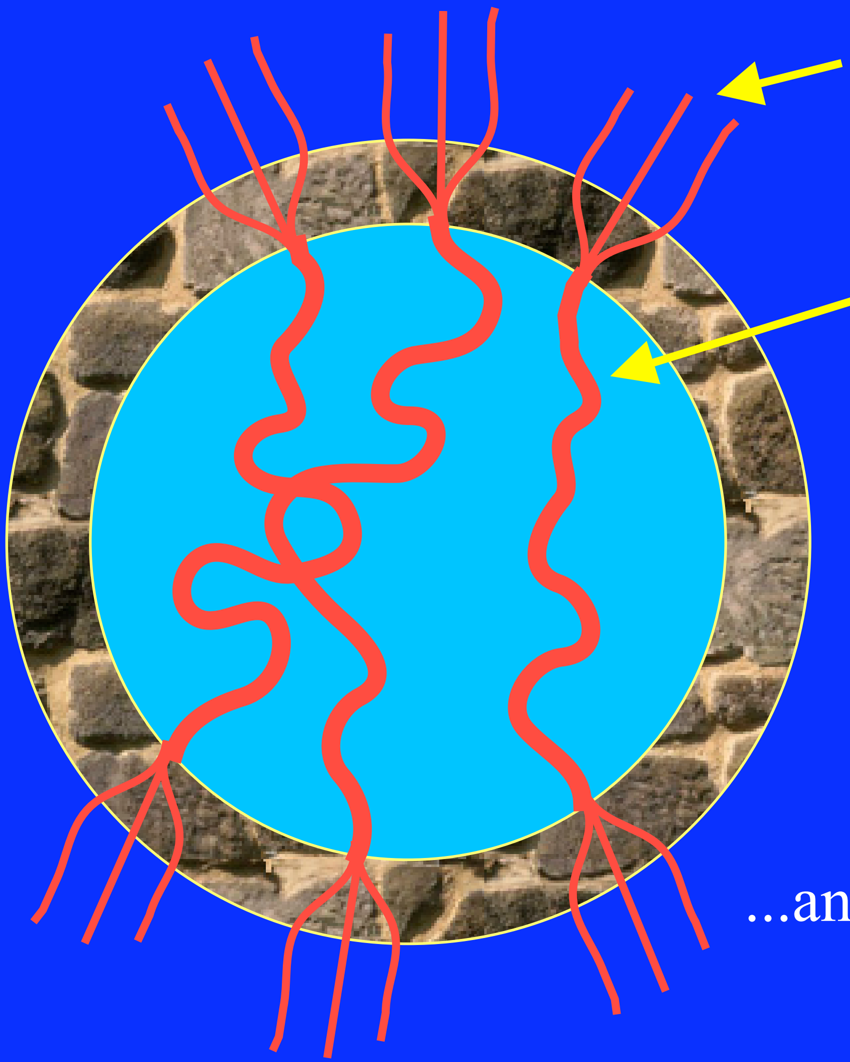
Rotating superfluid He



Distribution of vortices determines the fluid’s angular momentum.

A neutron star contains $\sim 10^{17}$ neutron vortices.

# Superconductivity in the core



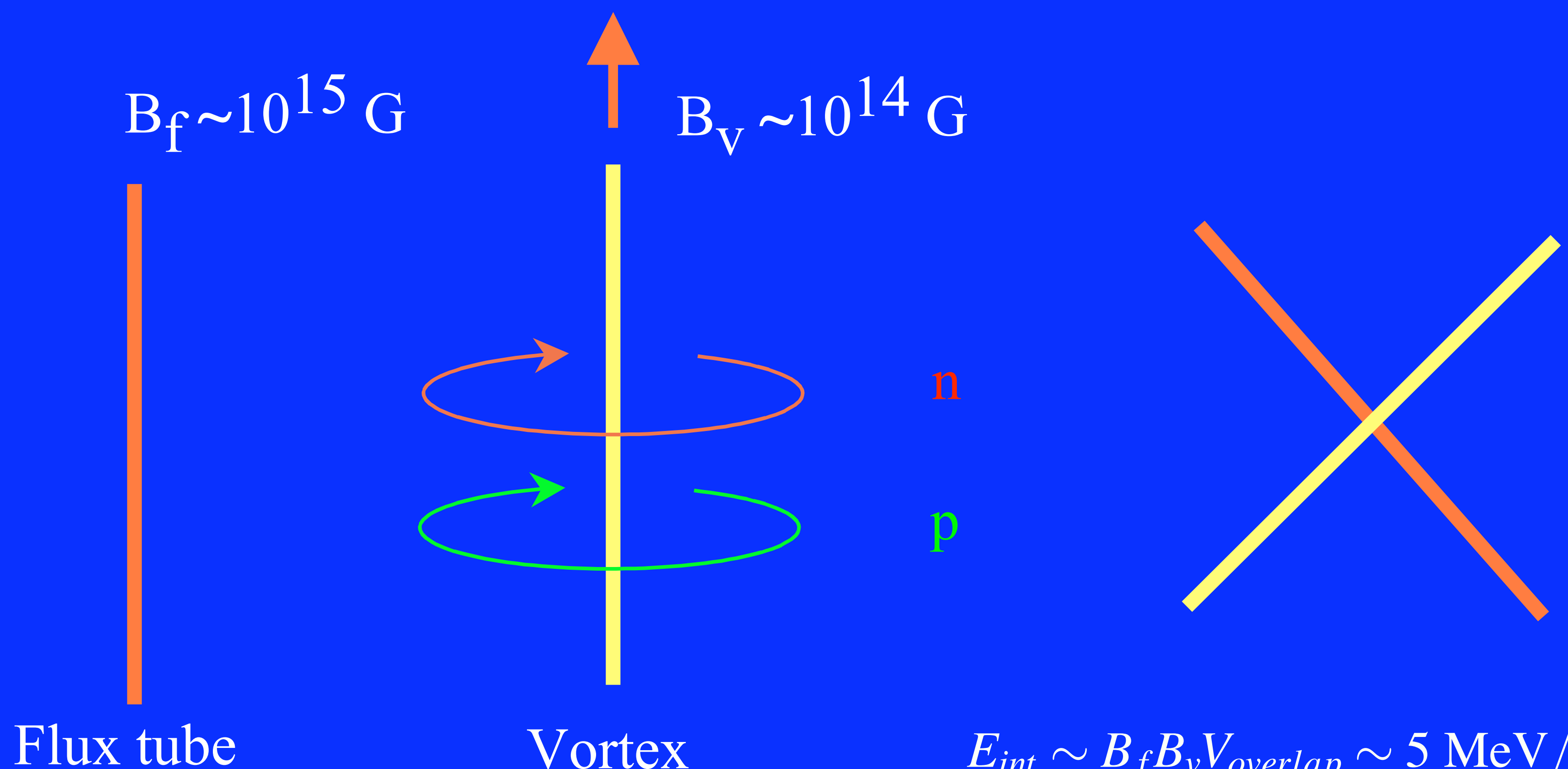

A neutron star contains $\sim 10^{31}$ flux tubes, frozen to the charged fluid.

...and far fewer neutron vortices, $\sim 10^{17}$.

The field structure is likely to have large toroidal components.

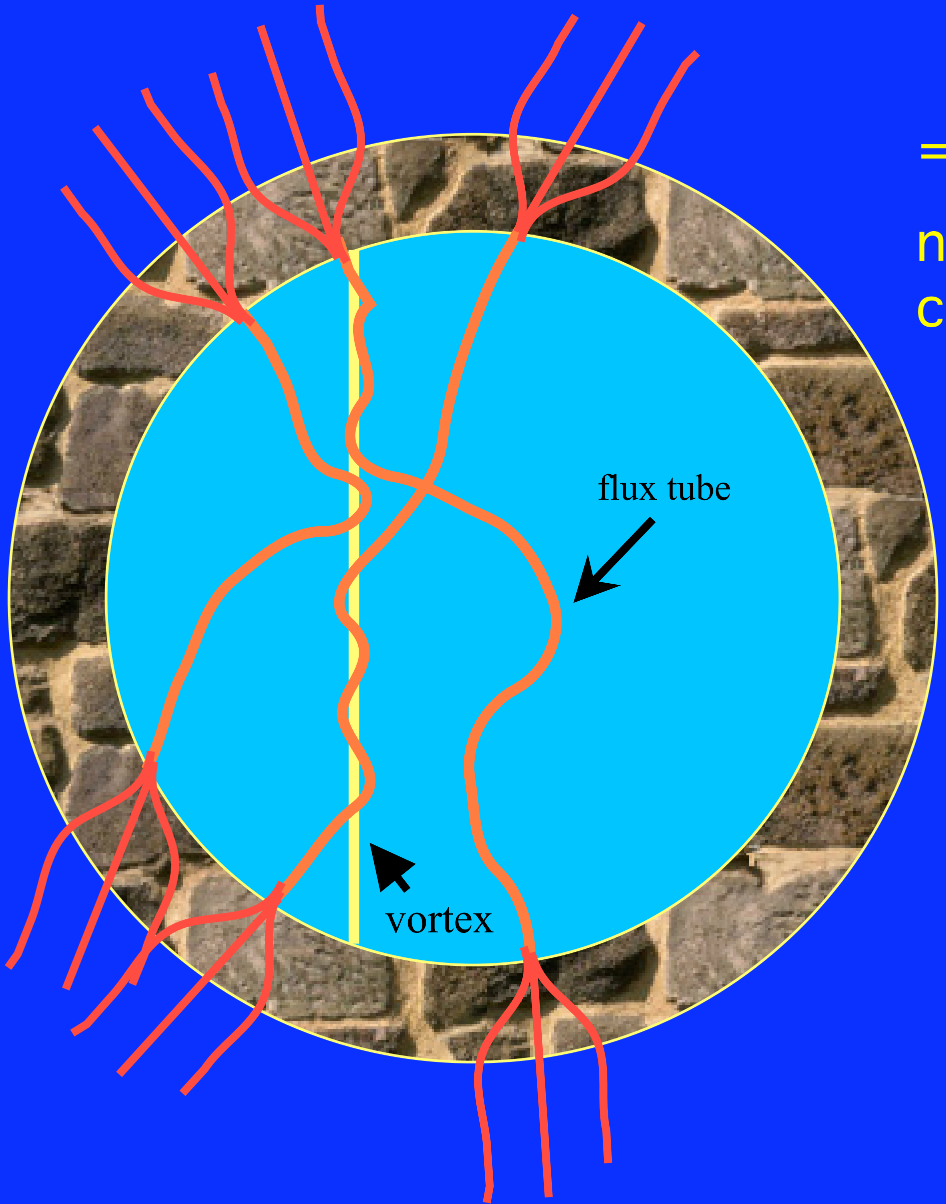
(e.g., Thompson & Duncan 1993; Ruderman et al. 1998).

# Vortices and flux tubes interact




$E_{int} \sim B_f B_v V_{overlap} \sim 5$ MeV/intersection

# Vortices are <u>pinned</u> to the flux tubes




⇒ angular momentum of the neutron fluid is fixed to the charged component plus crust.

How does this affect the precession dynamics?

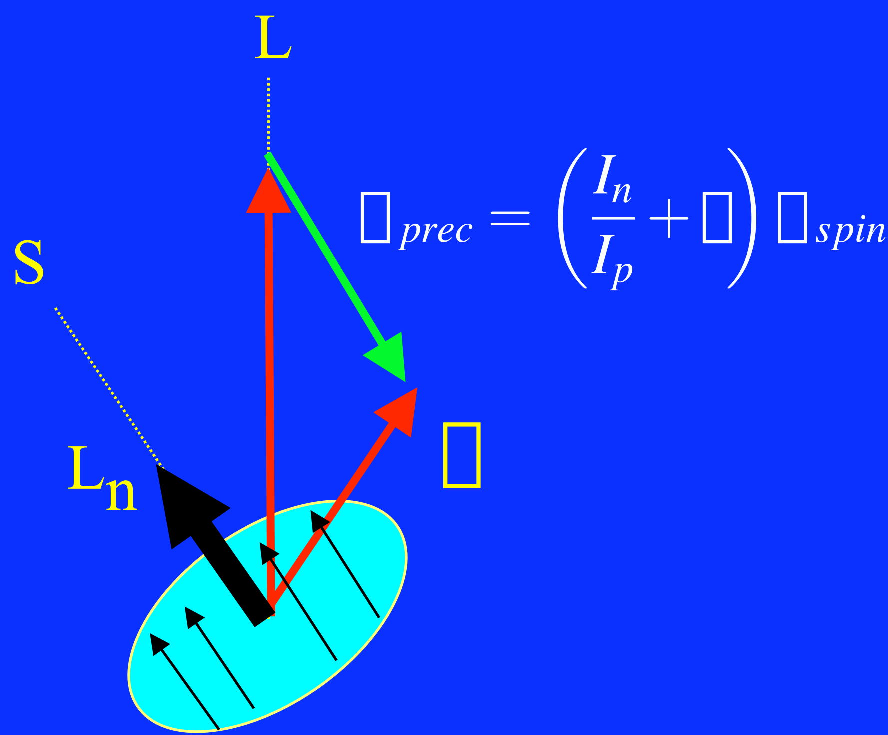
# Precession of the Crust Plus Core

(Link 2003)

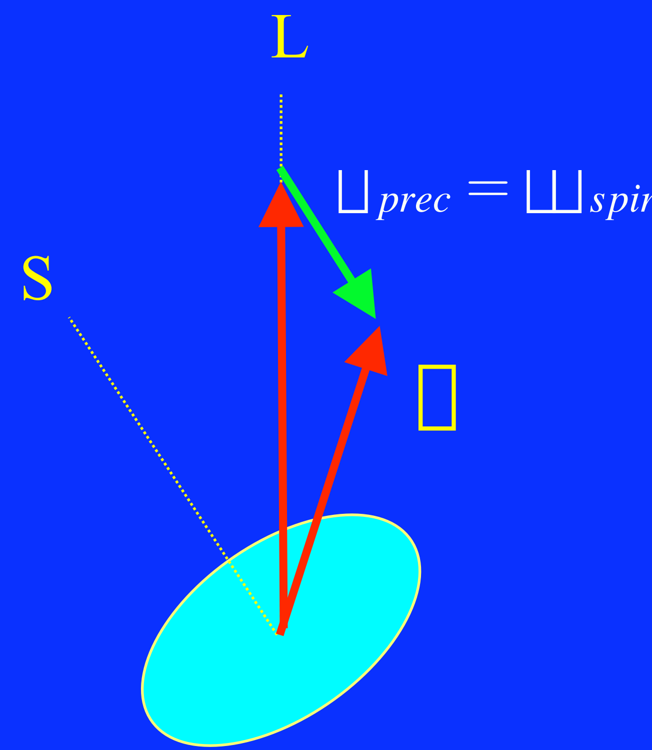
- Magnetic stresses enforce corotation between the crust and charges as a single “body”.
- The neutron superfluid's $\Omega_s$ cannot follow the body's $\Omega_b$; it is pinned to the body.

# If the pinning were perfect, precession would be very fast

(Shaham 1977)

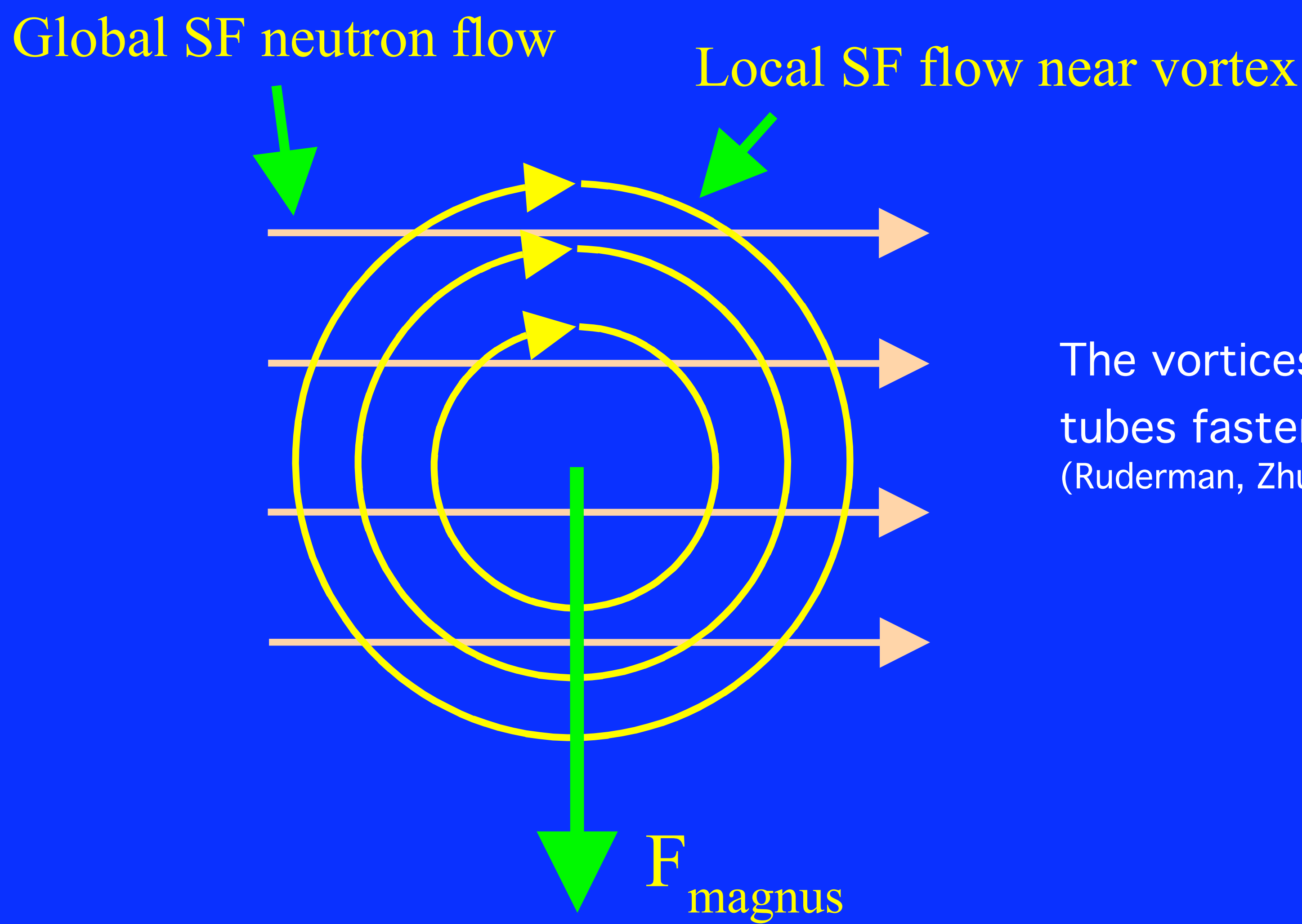



With pinning
(gyroscopic effect)



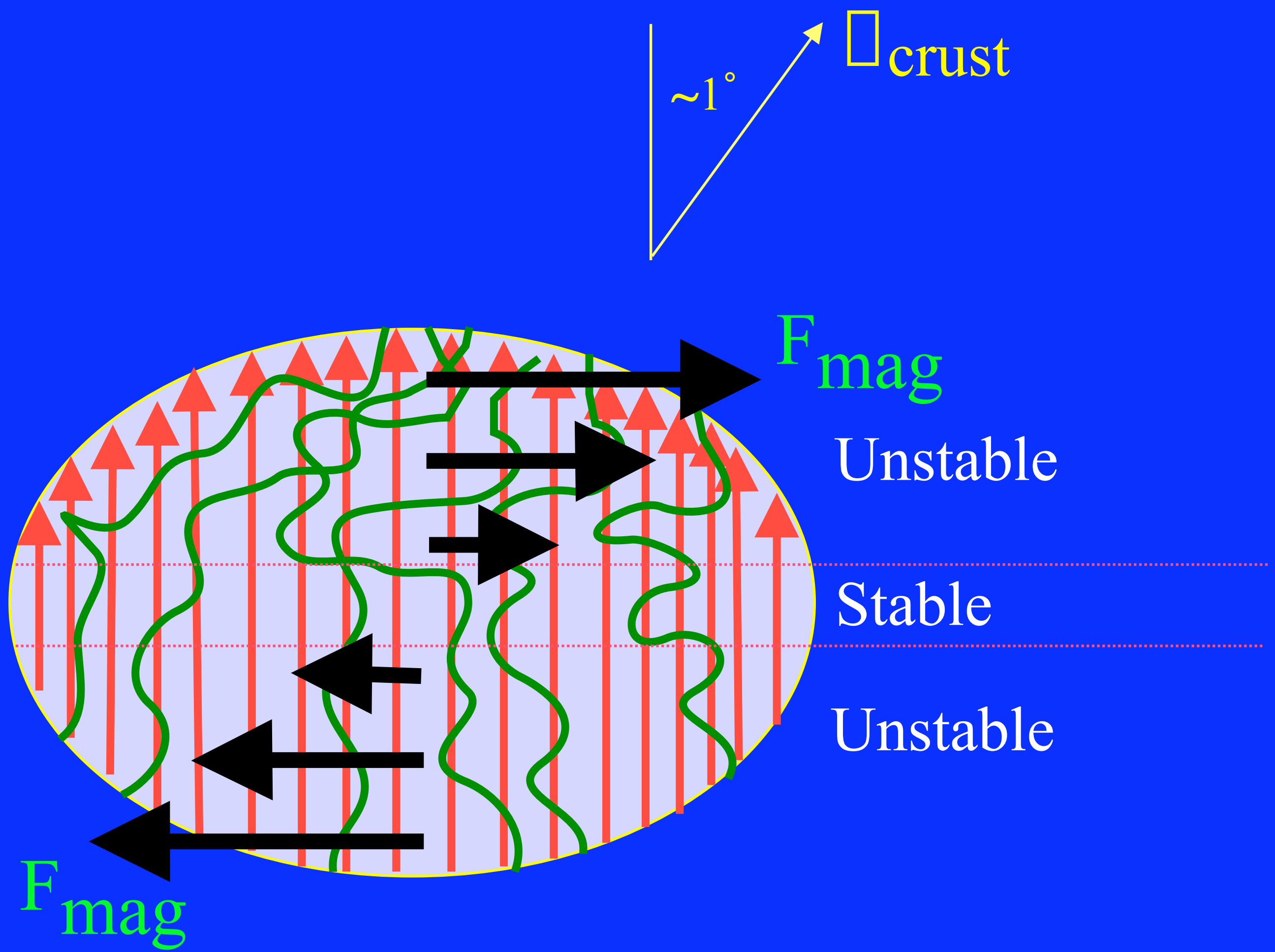

Without pinning

# As the star precesses, the vortices exert large forces on the flux tubes



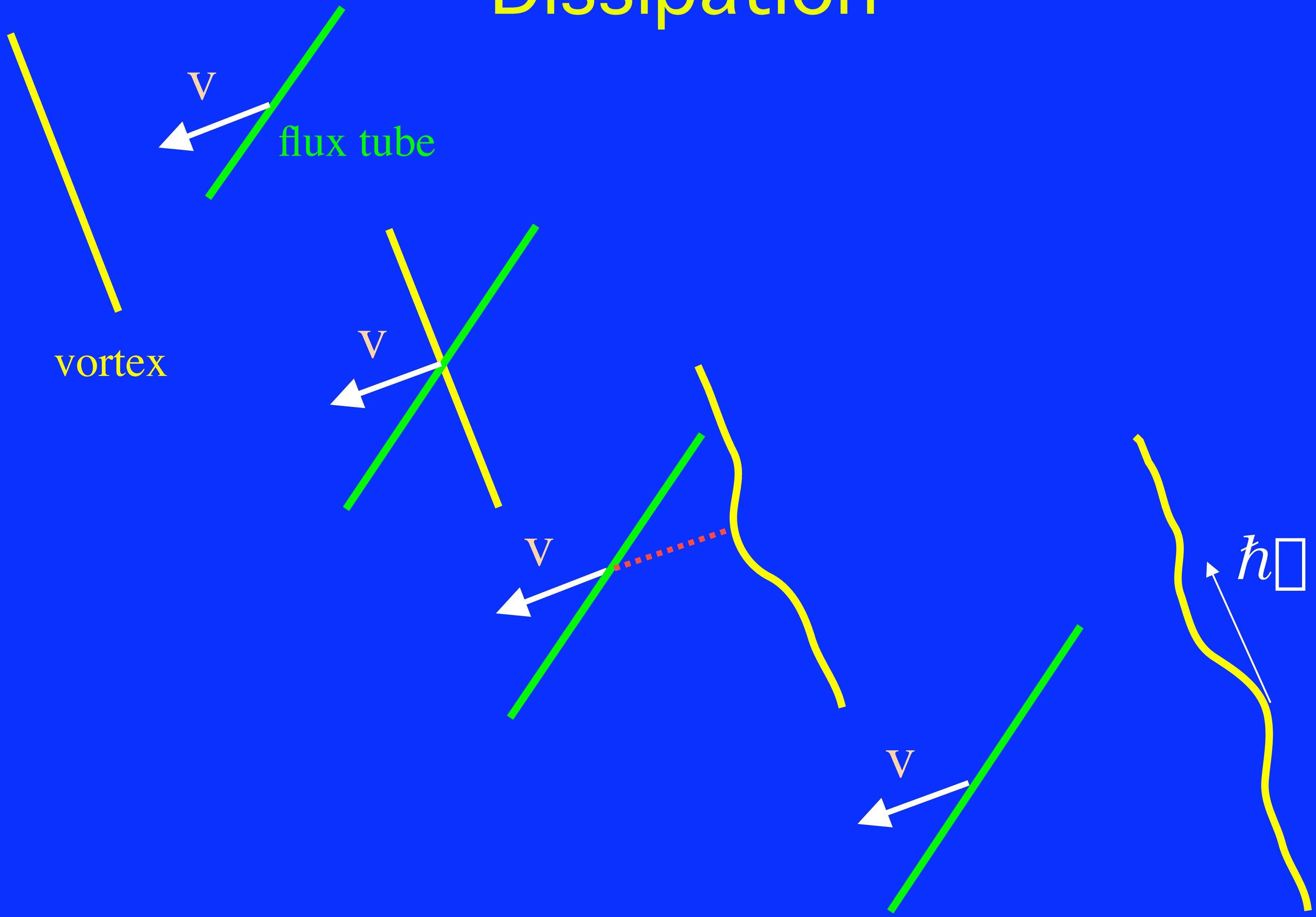

The vortices cannot push the flux tubes faster than $\sim 10^{-11}$ cm s$^{-1}$.
(Ruderman, Zhu, Chen 1998)

# The pinned state is <u>unstable</u>




*<u>Conclusion:</u>* most of the vortices are forced through the flux array.

# Dissipation

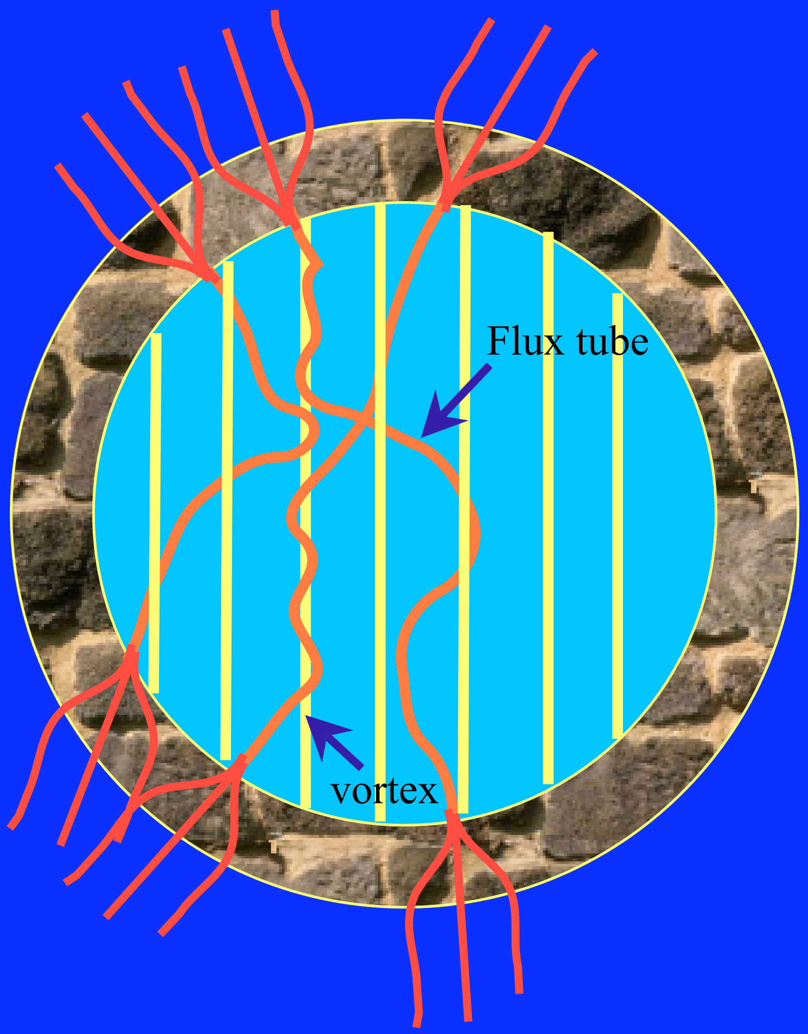


# Effects of dissipation through vortex excitation

(Link 2003)

- Dissipation damps the precession to very small amplitude in ~ 1 hr.
- In the new state, vortices are pinned to the vortices.
- The precession is fast, $p_{prec} < p_{spin}$ (<< 500 d), and of low amplitude (<<1$^\circ$). <u>Long-period, long-lived precession is not possible.</u>

Vortices and flux tubes cannot interact <u>anywhere</u> in the star.




What is wrong with this picture?

# Possible resolutions
# Some unlikely possibilities:

- Putative precession is not precession.
- The superconducting core has *no magnetic flux*.
- One or both of the hadronic fluids is not superfluid. *Contradicts pairing calculations.*
- The superfluid neutrons and superconducting protons coexist nowhere in the core. *Also contradicts pairing calculations.*

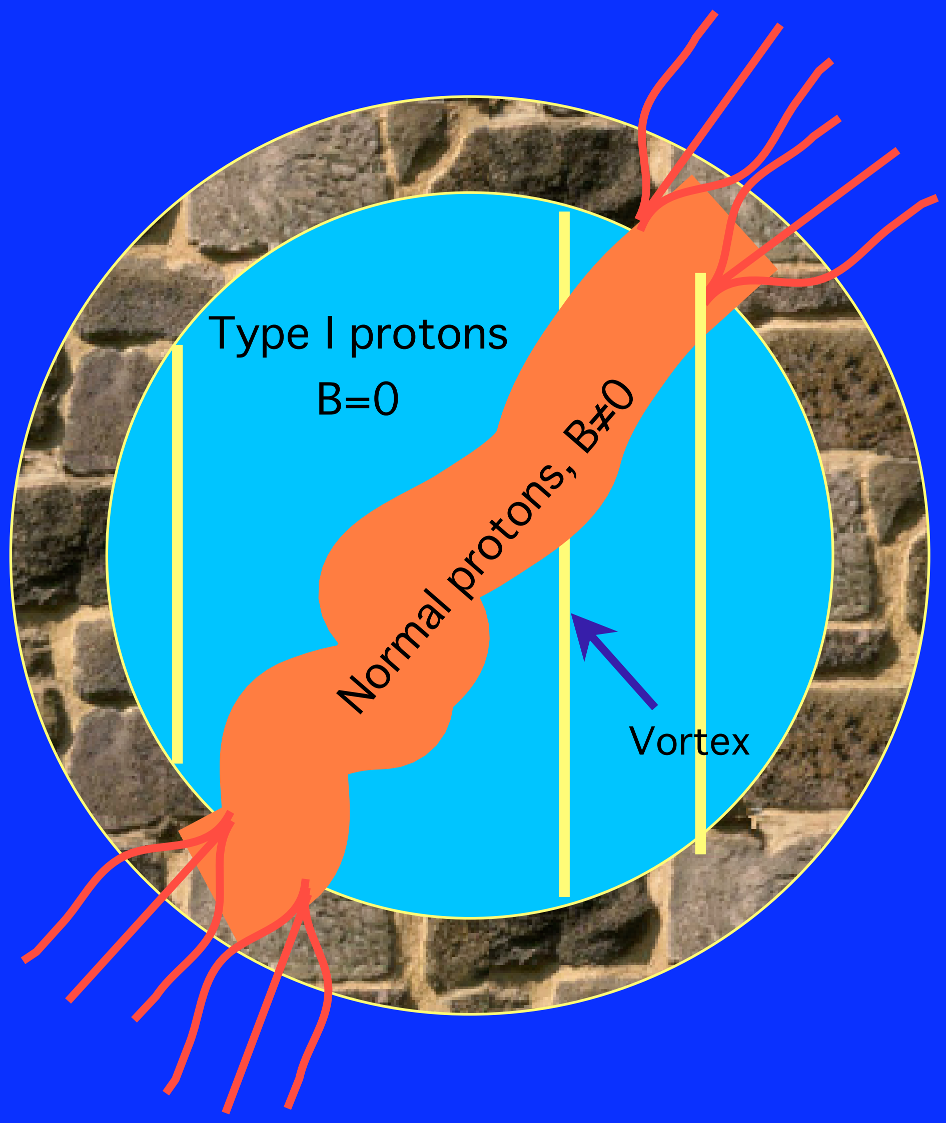
# A Strange Possibility

Neutron stars are actually strange stars.

(Later talks by Prakash, Glendenning, Alford, Vogt).

# A Reasonable Possibility

The core protons are a not a type II superconductor, but <u>type I.</u>




In this situation, the magnetic flux is not a significant impediment to vortex motion...

 <u>the crust could precess slowly.</u>

# If the core is a type I superconductor...

- URCA reactions which cool a neutron star could be faster.
- Glitch theories involving the core are not viable. (Inner crust theories remain viable).

# Conclusions

- Long-period precession of neutron stars provides a new probe of the state of the stellar core.
- The standard picture of coexisting vortices and flux tubes should be reconsidered.
- PSR B1828-11 might be providing the first evidence that the core is a type I superconductor, or lacking neutron vortices, or strange...